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Why wind power does not deliver the expected emissions reductions

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ABSTRACT

Debate has raged for decades on the role of carbon dioxide in climate change. It is often assumed that renewable energy technologies, because they are not powered by fossil fuels, will reduce CO_2s contribution to overall energy use. The unspoken hypothesis is that having these technologies replace coal, oil and natural gas will gradually lower the ambient level of CO_2, and thus alleviate or even eliminate possible climate change. However, a number of studies suggest because of the intermittent nature of some renewable technologies, CO_2 reduction will be less than presently anticipated by their proponents.

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1. Introduction

In the past few years, renewable energy sources, such as solar and wind, have made great inroads into the electrical grids of many European countries, such as Germany, Denmark and Spain. There is considerable public support for these policies, which include subsidies for installation and per unit energy output for these facilities. They are believed to reduce greenhouse gas (GHG) emissions that would otherwise be generated from fossil fuels used to generate electricity.

However, the data are not completely clear on this assumption. This paper explores whether GHG emissions are reduced by the use of renewables, and by how much. It also evaluates how much data would be required to give a definitive answer to this question.

A number of articles aimed at the public have suggested or implied that a unit of CO_2-free renewable energy will replace a unit of fossil-fuel energy, with its CO_2 emissions, almost one to one. For example, Greenspon [1] states,

> A study by Good Company, a sustainability consulting firm, claims that there is an 89% reduction of greenhouse gas emissions when replacing electrical power from the national grid with solar generated electricity.

However, this number is based on the assumption that solar energy replaces fossil-fuel energy on an equivalent basis, with no other effects on the grid [2].

2. Reliability, backup, storage, intermittency and variability

Certain renewables, such as geothermal and hydroelectricity, clearly reduce GHGs, because they are reliable and not intermittent. However, hydroelectricity production can be diminished substantially and thus become intermittent because of drought. This occurred in Venezuela, highly reliant on this source of electricity, in April 2010 [3].

Geothermal may also emit greenhouse gases, Axtmann [4] noted

> Geothermal steam at the world's five largest power plants contains from 0.15 to 30% noncondensable gases including CO_2,. . .Some CO_2 and sulfur emission rates rival those from fossil-fueled plants on a per megawatt-day basis.

Similar effects have been noted by Bergfeld et al. [5] in Nevada.

These two renewable systems store energy—in the case of geothermal, heat beneath the earth's surface, and in the case of hydroelectricity, behind a dam—which can be drawn upon to meet varying electricity load requirements. Although they are "natural", they contain inherent storage capacity.

This is not true for certain renewables, such as solar thermal, solar photovoltaic (PVs) and wind. Each of these is highly intermittent (the former two less so in certain desert areas), and do not have inherent storage capabilities. Solar thermal storage experiments were performed as early as almost four decades ago [6], but they have not proved economically feasible to date. In the technical term, some renewable energy is generally not dispatchable, i.e., an electrical utility cannot depend on a certain power level from these sources in the next hour or minute.

2.1. Storage

There are 17 pumped storage facilities described in a recent U.S. database [7]. These are the only large scale storage facilities associated with electric grids. In principle, they could store wind and other renewable energy. However, these facilities are geographically limited—they require two large reservoirs, one hundreds of feet above the other. It is not clear how many of the 17 are sufficiently close to potential wind and renewable energy sources to store some of their energy production.

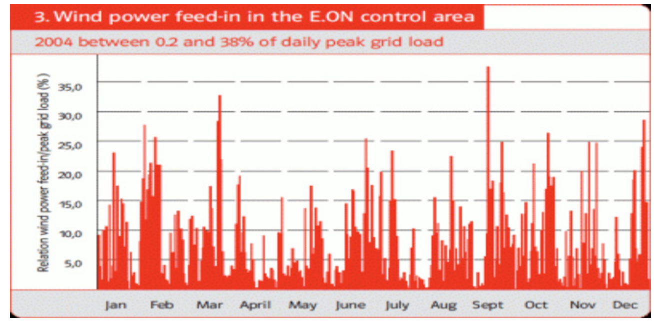

Fig. 1. Wind power production in the E.On Netz system covering much of Germany, 2004 [29].

2.2. Wind reliability

As Wang and Prinn [8] note, options to ensure reliability of wind power include (a) backup generation capacity, (b) long distance transmission lines extending over hundreds or thousands of kilometers, to take advantage of wind power from remote sites when local winds are temporarily calm), or (c) extensive energy storage capacity. Option (b) has been proposed from time to time, but would take switching and transmission capabilities which are apparently not presently available. Option (c) would require overcoming the substantial economic cost of storing electricity.

An example of wind variability in Germany in 2004 is shown in Fig. 1, taken from an E.On Netz report. It is sometimes suggested that if the wind stops blowing in one location, it may be blowing in another location some kilometers or tens of kilometers away, thus providing an averaging function and reducing variability. However, the E.On Netz "wind turbines are spread out over all of Germany, from Bavaria in the South to offshore in the German Bight in the North" (de Groot and le Pair). Fig. 1 shows that there is still substantial intermittency over this large area.

2.3. Backup

In their discussion of future renewable deployment, Baker et al. [9] note,

> The baseline approach assumes a need for backup electricity generation. As the percentage of electricity produced from PVs {photovoltaics] increases, backup power is required to ensure grid reliability. For this analysis, one-to-one backup is required when electricity production capacity from PVs is 20 percent of total capacity in any region.

A second regime considered by Baker et al. assumes no backup, but a zero-cost storage device. Such a device is presently not available.

This point is reiterated by the report *Powering the Future*, by the consulting firm Parsons Brinckerhoff (as mentioned in [10]). It states that

> Over-reliance on wind power could scupper [British] government plans to cut carbon emissions by 2050, consultant Parsons Brinckerhoff warned this week.

The firm warned that extra back-up power generation capacity would be needed to pick up shortfalls in wind generated electricity during calm weather. The most cost effective and fast response solution would be gas fired power stations, but these generate high levels of CO_2.

Fig. 2. Schematic graph of miles per gallon for the 2011 Toyota Camry, the best-selling automobile in the U.S. Mileage on the highway is about 32, and for city driving, about 22.

2.4. *Renewable failures*

While all energy systems can have unexpected failures, some renewables have unusual difficulties. A story in February 2010 noted that eleven wind turbines from California were apparently frozen in place for two months in frigid Minnesota [11].

On the opposite end of the spectrum, when wind produces more power than the grid can accommodate, wind farm operators in Britain are paid to shut down operations [12].

3. Estimating CO_2 reductions in various locations

3.1. *Cycling and automobile fuel efficiency*

As will be noted below, cycling (increasing and decreasing power output from (mostly) gas-fired turbines) increases CO_2 production. The analogy can be drawn with auto fuel efficiency. In the U.S, all new passenger vehicles are required to post estimated miles per gallon on their windshields. But rather than one number, two are shown. The first is for city stop and go driving. The second is for highway driving, where brakes are used only infrequently. While the ratio of highway miles per gallon to the corresponding city mileage varies from one manufacturer to another, the ratio is as high as two, and rarely below 1.3. This shows that city driving efficiency is much less than that of highway driving. Typical results for a well-known automobile are shown in Fig. 2. The same principle applies to the cycling of fossil-fuel plants caused when intermittent sources of power enter the electrical grid.

3.2. *Gross report*

One of the most influential studies stating that renewables do reduce GHGs is by Gross et al. [13]. They state,

> . . .it is unambiguously the case that wind energy can displace fossil fuel-based *generation*, reducing both fuel use and carbon dioxide emissions (p. iii)

However, this statement does not specify a best value or range for the projected reductions of GHGs.

Table 3.8 of this study gives the percentage savings of GHGs for ten studies out of the hundreds discussed by Gross. However, the percentage values range from zero to 48%, indicating an extremely wide range. As well, it is not clear which of the estimates are based on actual measured data over a long period of time, and which are theoretical constructs. As the authors note (p. 59),

> Almost all of the literature deals with the impacts of intermittency using a statistical representation of the main factors, or through simulation models based upon statistical principles.

In a lengthy document (about 100 pages), Gross et al. do not show one set of data on actual carbon dioxide reductions, although electric utilities know hour by hour how much fossil fuel they use. As well, it is not clear if any of the authors quoted by Gross had experience operating electrical grids.

3.3. *Bonneville Power Authority (BPA)*

Lowe [14], in discussing the use of new natural gas facilities by Bonneville Power Authority in the U.S. Northwest to balance wind power generation, states,

> . . .natural gas facilities produce greenhouse gas emissions, which at least partly negates the purpose of the renewable energy mandates. When asked if wind power was reducing carbon emissions, Deb Malin, a BPA representative, answered, “No. They are, in fact, creating emissions.” This is because when a natural gas facility is ramped up and down to respond to fluctuations in wind power output, it can see its efficiency drop to between 35–50 percent.

This suggests that CO_2 emissions could increase, rather than decrease, due to the introduction of wind power. BPA is one of the largest U.S. utilities, so its results have broad implications. However, the statement is not quantitative. Only when BPA data on CO_2 reductions (or increases) are available can the validity of this statement be assessed.

3.4. *E.On Netz report*

By the end of 2004, Germany had an installed wind farm capacity of over 16,000 MW. This made Germany the world’s leader in total wind energy capacity [29]. This utility managed one third of the world’s wind energy at that point, and thus had more experience with this energy form than any other.

They conclude (Summary),

> . . .traditional power stations with capacities equal to 90% of the installed wind power capacity must be permanently online in order to guarantee power supply at all times

This implies that any carbon dioxide reduction would be at most 10%. The report goes on to say that based on the projected increase in German wind energy, the relative contribution of wind to guaranteed capacity will drop to 4%, implying a decrease in carbon dioxide of about the same percentage.

Wind and solar can be highly variable. E.On Netz notes (Fig. 6)

> The feed-in capacity can change frequently within a few hours. This is shown in Figure 6, which reproduces the course of wind power feed in during the Christmas week from 20 to 26 December 2004. Whilst wind power feed-in at 9.15 am on Christmas Eve reached its maximum for the year at 6,024 MW, it fell to below 2,000 MW within only 10 hours, a difference of over 4,000 MW. This corresponds to the capacity of 8 × 500 MW coal fired\power station blocks. On Boxing Day (Dec. 26}, wind power feed-in in the E.ON grid fell to below 40 MW.

3.5. *The Danish experience*

A major report from Denmark [15], perhaps the nation most committed to renewables in the form of wind, states,

> Wind energy has replaced some thermal generation in Denmark. It has saved about 2.4 million metric tons of carbon dioxide a year.

We can compare this value to the gross output of carbon dioxide from Denmark, according to the U.S. Energy Information Administration [27]. Denmark averaged 10.1 billion kWhr from 2006 to 2008 generated from wind. Total net generation was about 40 billion kWhr over the same period, so wind accounted for about one-quarter of total generation, the highest in the world.

From 2004 to 2006, the average net emission of carbon dioxide was 55.9 million metric tons, so the savings was 2.4/55.9, or about 4%. This is in accordance with the projections quoted from E.On Netz elsewhere in this paper, which estimated a 4% decrease in carbon dioxide emissions for a major penetration of wind into the grid system in Germany.

3.6. Bentek: Colorado

Bentek [16] took a different approach in studying emissions in Colorado. The process by which generation is ramped up and down at a plant due to wind or any other factor is called *cycling* (p. 23).

> [Coal] cycling makes coal generating units operate much less efficiently. . .so inefficiently, that these units produce significantly greater emissions (p. 1).

> incidence of coal cycling is common and has risen sharply since introduction of wind generation, and in 2008 and 2009 the result has been significantly greater emissions of SO_2, NO_X and CO_2 than would have occurred if the coal units had not been cycled. (p. 46).

How do these considerations affect GHG emissions? The study uses three methods to estimate reductions or increases in CO_2. Method C (p. 40) is, in the authors' view, the most realistic, taking account of the cycling discussed above. They find that CO_2 emissions increased by about 2% when wind is part of the energy mix. They state,

> The net result is that cycling Cherokee [power plant] on July 2 [2008] resulted in greater emissions even netting the emission[s] avoided by using wind.

This then suggests that CO_2 emissions can rise, not fall, when wind energy is used in the electrical grid.

3.7. Bentek: Texas

Bentek also considered data from ERCOT, the Electrical Reliability Council of Texas (p. 56). They note,

> . . .while the scale of wind, gas and coal operations in ERCOT is larger than in PSCO's [Public Service of Colorado] territory, the result is the same.

Bentek estimates 2% savings of CO_2 production at the J. T. Deeley plant in Texas due to cycling, a reversal of sign compared to Colorado. However, the authors do not specify how much wind energy was generated in that area for that reduction.

On p. 68, the report states

> CO_2 emissions were higher in 2009 by between 0.8 and 1.1 thousand tons in 2009 and ranged from a very small savings to 0.6 thousand tons incremental emissions in 2008. The range amounts to less than 1% of total CO_2 emissions in either year.

There are often severe data limitations in determining how much GHGs are reduced (or even in some cases, increased) by the use of wind energy. A number of utilizes decline to allow access to data that can allow a determination of the extent of CO_2 reduction. Bentek (p. 46) found for Colorado,

> . . .it is not possible to understand precisely the interaction between wind generation and coal plant cycling in PSCO's (Public Service Company of Colorado) territory because PSCO will not release its hourly wind generation data.

3.8. The White compilation

White [17] has gathered data from a variety of sources. He notes,

> There is no CO_2 saving in Danish exchange with Norway and Sweden because wind power only displaces CO_2-free generated power. When the power is consumed in Denmark itself, fluctuations in wind output have to be managed by the operation of fossil-fired capacity below optimum efficiency in order to stabilise the grid (i.e., spinning reserve). Elsam, the Jutland power generator, stated as recently as May 27th at a meeting of the Danish Wind Energy Association with the Danish government that increasing wind power does not decrease CO_2 emissions. Ireland has drawn similar conclusions based on its experience that the rate of change of wind speed can drop faster than the rate at which fossil-fuelled capacity can be started up. Hence spinning reserve is essential, although it leads to a minimal CO_2 saving on the system[1]. Innogy made the same observation about the operation of the UK system [18].

In another document, White states,

> renewable electricity has become synonymous with CO_2 reduction. However, the relationship between renewables and CO_2 reduction in the power generation sector does not appear to have been examined in detail, and the likelihood, scale, and cost of emissions abatement from renewables is very poorly understood.

He goes on to say (p. 5),

> the CO_2 saving from the use of wind . . . is probably much less than assumed by Government advisors, who correctly believe that wind could displace some capacity and save some CO_2, but have not acknowledged the emissions impact of matching both demand and wind output simultaneously. As a result, current policy appears to have been framed as if CO_2 emissions savings are guaranteed by the introduction of wind-power, and that wind power has no concomitant difficulties or costs. This is not the case.

3.9. U.S. National Academy of Sciences

Droz [19] quotes the U.S. National Academy of Sciences as saying,

> Projections for future wind energy contributions to reduction of air-pollutant emissions in the U.S. are highly uncertain. . . . Using the future projections . . . the committee estimates that wind energy development probably will contribute to offsets of approximately 4.5 percent in U.S. emissions of CO_2.from electricity generation by other electricity-generation sources by the year 2020. [20]

This is comparable to the estimate for Danish reductions, mentioned elsewhere in this study.

3.10. German study

A 2005 German study [21] from a consortium of five energy and policy organizations estimated that CO_2 savings in 2007 would

[1] Data available on http://www.esb.ei.

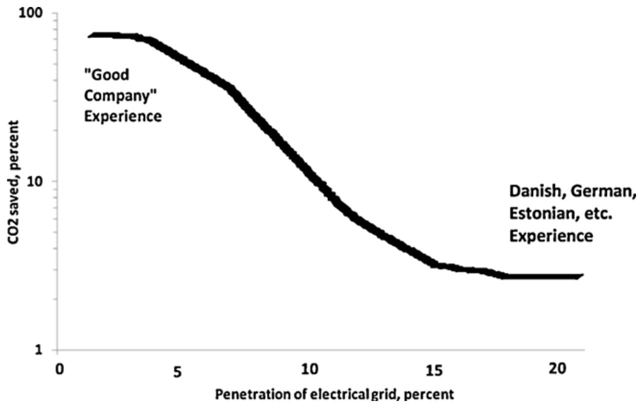

Fig. 3. A schematic graph of CO_2 reductions as a function of wind (or other intermittent renewables) penetration into an electrical grid. Penetration is defined as the average fraction of energy contributed by wind to overall energy consumption. As shown in Fig. 1, dealing with a large German system, that fraction varied over time from 38% to almost zero.

be 5–9 million metric tons. CO_2 emissions from the German energy sector (power stations and thermal power stations) was 385 million metric tons in 2003 [26]. This then implies a CO_2 saving of 1–3%. As a confirmation of this low fraction [22], Germany's leading weekly magazine notes,

> Despite Europe's boom in solar and wind energy, CO_2 emissions haven't been reduced by even a single gram. Now, even the Green Party is taking a new look at the issue—as shown in e-mails obtained by SPIEGEL ONLINE. . .Even more surprising, the European Union's own climate change policies, touted as the most progressive in the world, are to blame. The EU-wide emissions trading system determines the total amount of CO_2 that can be emitted by power companies and industries. And this amount doesn't change—no matter how many wind turbines are erected.

3.11. Ireland

Reductions of CO_2 emissions in Ireland have also been discussed [23].

> . . .to accurately quantify the emissions saving which can be derived from WPG [Wind Powered Generation] the growing inefficiency of the conventional plant portfolio must also be taken into account. It is not sufficient to estimate the amount of energy which can be obtained from a given capacity of WPG, and to assume that the equivalent percentage of fossil fuel and therefore CO_2 can be avoided. This ignores the impact of the increasing number of startups and lower capacity factor as WPG increases. (p. 33)

The authors estimate that a wind capacity of 400 MW (about one-tenth) of Ireland's power capacity at the time of writing would reduce CO_2 emissions by 5.4% (p. 33). The study estimates a CO_2 reduction of 12.9% for a 30% penetration of wind, stating, "This quantifies the growing inefficiency in using WPG to curtail emissions."

This increase in percentage of CO_2 reduction with increased penetration of wind differs from other sources quoted here, which estimate decreased CO_2 reduction with increased penetration.

3.12. Estonia

The Tallinn Technical University of Estonia stated [28]

> The fuel economy and emissions reduction in the power systems consisting mainly of thermal power plants are not proportional with the electricity production of wind turbines. . .In reality, only keeping the necessary additional reserve capacity will increase the fuel consumption (emissions) by up to 8.1%. To get a more realistic fuel consumption (emissions) estimate that considers also fluctuations of wind power reduced to the mean power of windmills, the initial fuel consumption curve should also be raised by 8.1%. The calculations were repeated for several values of power system load and the results showed at least 8-10% increase of fuel consumption and emissions compared with the steady operation of thermal stations under constant mean power of wind turbines. In some cases the environmental gain from the wind energy use was lost almost totally.

4. Conclusions

de Groot and le Pair [25], after noting that the efficiency of back-up and reserve fossil fuel plants can increase, not decrease, the amount of CO_2 produced when wind is part of the energy mix, state,

> It is necessary to establish on the basis of data, rather than model predictions, the level of extra fuel use caused by decreased efficiency of fossil back-up for wind power, before countries translate large investment plans in wind energy into reality.

This lack of data was noted by Gross et al. [13], who stated that his compilation of papers dealing with CO_2 savings was based almost entirely on statistical calculations. Since utilities generally know from hour to hour their expenditures on fossil fuels, there should be a concerted effort on their part to supply this data to researchers and policymakers.

A likely schematic scenario for CO_2 saving as a function of wind (or other intermittent renewable energy source) penetration into the electrical grid is shown in Fig. 3. The vertical scale is logarithmic, indicating substantial decreases in savings as penetration increases linearly. When penetration is very small, as in the case of the Good Company solar installation mentioned by Greenspon [1], CO_2 savings are close to 100%. (In this case, the savings were listed as 89%, because about 11% of CO_2 was expended in mining, fabrication, construction and transportation of the installation).

As the penetration increases, the savings decrease, due to the cycling mentioned above. On the right hand side of the graph is the Danish, German and Estonian experience, with a penetration of about 20% and a saving of CO_2 of a few percent (4% in the case of Denmark).

There are considerable uncertainties about how fast this decrease occurs, and the curve in Fig. 3 should be taken as only suggestive. However, the arc seems to be a mirror image of a sigmoid curve, with an equation

$$Q = \frac{200}{1 + e^{cx}}$$

where Q is the CO_2 reduction in percent, x is the wind or intermittent renewable penetration of the grid in percent, and c is a constant, of the order of 0.2 in Fig. 3.

5. Uncertainties

There are considerable uncertainties in developing a curve of this type. A few of the many, not necessarily in order of importance, are:

(a) The mix of fossil fuels used in the grid and the type of gas turbines in particular;
(b) Some of the literature on wind is of a polemic nature, either advocating its widespread use or pointing out its deficiencies.

Care has to be taken to concentrate on the facts and leave opinions aside;

(c) Whether renewable energy is exported to other countries, as in the case of Denmark [15]. This could skew results;
(d) The number of cycles of the fossil fuel sources that take place over time;
(e) What fraction of fossil fuel plants in the grid are relatively inefficient open-cycle gas turbines (as opposed to more efficient closed cycle gas turbines);
(f) The carbon dioxide intensity emitted from the fossil fuels used in the grid;
(g) The degree of variability of wind resources over a period of time, and a host of others.
(h) Funding sources for some literature is sometimes from proponents or opponents of the energy source;
(i) Some of the literature is not peer reviewed, posing potential problems in quality control.

No attempt is made here to classify the literature quoted on the nine dimensions mentioned here. However, it is of interest to note that the range of CO_2 savings mentioned in the detailed study by Gross et al. [13], 0–48%, is within the uncertainties attributable to Fig. 3.

6. Future data requirements

Since many electrical utilities in North America and Europe have at least some wind or other intermittent energy sources (some, like ERCOT, in the U.S., with substantial penetration), in principle the fraction of CO_2 reduction with increasing penetration could be calculated over utilities and nations. This would allow the extensive theoretical estimates that have been performed over the years to be carefully evaluated. In addition the effect on policies dealing with climate change, where some nations propose to reduce CO_2 emissions by 80% by the year 2050, could be more accurately calculated.

Are there any solutions to the possible increase of CO_2 emissions due to cycling? Backman states [24],

> When the load reduces in the evening and at night, flexible assets are dropped off in favour of less flexible baseload assets such as coal. However, the wind typically blows at these times, essentially hitting at the worst time of the day in terms of system stability. This is where flexible reciprocating engine-based plants can be useful.
>
> These flexible gas engine plants can start-up in ten minutes to provide non-spinning reserve, and could in the future be tuned to start up in as fast as five minutes, if the requirements for this product change.

However, it is unclear how these types of gas engine plants will affect the overall emissions of CO_2. It is also unclear how they differ from existing or proposed gas turbines.

7. Summary

It is frequently claimed, in the scientific or popular literature, that introduction of wind and other intermittent energy sources into utility and national electrical grids will substantially, if not completely, decrease CO_2 emissions from fossil fuel sources. While wind power certainly has desirable attributes, this paper, based on data from two continents and a variety of sources, suggests that as wind penetration increases, the CO_2 reduction will gradually decrease due to cycling of the fossil fuel plants that make up the balance of the grid.

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